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VOLUME 2 OF 2
GARRETT 21-4314-2

MATERIALS FOR ADVANCED TURBINE ENGINES

PROJECT COMPLETION REPORT
PROJECT 3

LOW-COST, SINGLE-CRYSTAL TURBINE BLADES

VOLUME 2

by
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FOREWORD

This Project Completion Report was prepared for the National Aeronautics and Space Administration, Lewis Research Center. It presents the results of a program conducted to establish exothermic heated casting technology for the manufacture of low-cost, single-crystal, uncooled turbine blades for gas turbine engines. The program was conducted as part of the Materials for Advanced Turbine Engines (MATE) Program under Contract NAS3-20073. This is Volume 2 of the Project Completion Report, covering the performance and endurance engine testing and post-test component analysis.

The authors wish to acknowledge the assistance and guidance of S. Grisaffe and R. L. Dreshfield of the NASA-Lewis Research Center in successfully completing this project.

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SECTION I

1.0 SUMMARY

The demand for more efficient and economical engines continues to push the industry toward higher turbine operating temperatures. The ability to maintain this trend is strongly tied to advancements in material technology. Single-crystal (SC) castings offer many significant advantages, such as higher melting point and higher strength, over turbine materials currently used in production engines. The goals of MATE Project 3 were to develop a low-cost casting process capable of producing SC turbine blades and to demonstrate the capability of the SC blades through extensive property, rig, and engine testing.

The following accomplishments are the most significant program goals achieved:

- o Incorporating the MATE high-pressure (HP) turbine blades and support hardware into the test engine reduced TSFC by 1.4 percent and T_5 (interturbine temperature) by 2.5 percent, compared to the baseline engine with uncooled directionally solidified (DS) HP turbine blades

- o The MATE single-crystal turbine blades, both NASAIR 100 and Alloy 3, successfully completed over 200 hours of endurance engine testing with no signs of distress

- o The exothermic casting process was successfully developed into a low-cost nonproprietary method for producing single-crystal castings.

Project 3 was divided into seven tasks. In Task I, the exothermic casting process was modified to consistently produce

acceptable solid SC high-pressure turbine blades for the TFE731 turbofan engine. This effort focused on the castability and baseline mechanical properties of blades produced with MAR-M 247.

During Task II, SC alloy derivatives of the MAR-M 247 alloy were assessed for castability, microstructure, and improvements in mechanical properties. Two of these SC compositions, NASAIR 100 and Alloy 3, were selected for detailed characterization.

In Task III, mechanical, environmental, and physical properties of SC NASAIR 100 and Alloy 3 were quantified. Mechanical property testing included creep rupture, tensile, and high- and low-cycle fatigue, and the determination of the effects of protective coatings. Environmental characterization included coated and uncoated oxidation and hot-corrosion tests. Physical properties measured included density, elastic modulus, thermal expansion, and thermal conductivity.

The SC HP turbine blade was designed in Task IV to utilize the improved mechanical properties of the prime SC alloy (NASAIR 100).

During Task V, two full sets of SC turbine blades and the required support hardware for both rig testing and the Task VI engine testing were manufactured. Rig and bench testing were also completed in Task V.

The results of the first five project tasks and the achievement of their related goals are presented in Volume 1 of the Project 3 Final Report (CR-168218, Garrett No. 21-4314-1). The results of the final two tasks--Task VI Engine Testing and Task VII Post-Test Evaluation--are presented in this document (Volume 2).

The Task VI Engine Testing was successfully completed. Testing consisted of back-to-back performance testing of a production configuration TFE731 engine with uncooled DS HP turbine blades and the same engine with the uncooled MATE SC HP turbine blades and related support hardware. This testing showed that the MATE engine configuration reduced TSFC by 1.4 percent and T_5 by 2.5 percent. Performance testing was followed by 200 hours of endurance engine testing, divided into the following four 50-hour segments:

- 50-hours of high-cycle-fatigue (HCF) evaluation
- 50 hours of maximum power (stress-rupture evaluation)
- 50 hours of simulated commercial mission
- 50 hours of low-cycle-fatigue (LCF) evaluation.

None of the blades subjected to the 200 hours of engine testing visually showed any detrimental effects from the testing. This was verified by the post-test metallurgical evaluation performed in Task VII.

SECTION II

2.0 INTRODUCTION

The NASA Materials for Advanced Turbine Engines (MATE) Program is a cooperative effort with industry to accelerate introduction of new materials into aircraft turbine engines. As part of this effort, Garrett Turbine Engine Company (GTEC) was authorized under NASA Contract NAS3-20073 to develop a new technique for manufacturing low-cost, single-crystal (SC), uncooled cast turbine blades to reduce SC casting costs and improve fuel consumption in advanced turbofan engines. The process development included those efforts required to transfer the technology from the previously demonstrated feasibility stage through component demonstration and engine test. Portions of the overall effort included process scale-up, alloy evaluations, mechanical property generation, hardware procurement, component testing, and full-scale engine testing to evaluate potential benefits.

This report constitutes Volume 2 of a two-volume Project Completion Report presenting the results of the investigations and tests performed under MATE Project 3, Low-Cost Single-Crystal Turbine Blades. This volume covers only the Project 3 full-scale engine testing and post-test analysis. All other aspects of this project are covered in Volume 1 of this report.

The intent of Project 3 was to develop a low-cost process to produce single-crystal, uncooled turbine blades and to design and substitute this blade for the solid, directionally solidified (DS) turbine blade used in the high-pressure turbine of the GTEC TFE731 turbofan engine.

Project goals associated with this program included the following:

- Development of a nonproprietary, low-cost SC casting process
- Improvement of the stress-rupture capability of the SC alloys relative to DS MAR-M 247
- Design of an uncooled HP turbine blade to use the SC material
- Demonstration of uncooled SC turbine blades through component and engine testing.

Project 3 was subdivided into the following seven tasks:

Task I	-	Casting Technology
Task II	-	Alloy/Process Selection
Task III	-	Property Characterization
Task IV	-	Blade Design
Task V	-	Component Manufacture and Testing
Task VI	-	Engine Testing
Task VII	-	Post-Test Evaluation

Tasks I through V are covered in detail in Volume 1 of this Project Completion Report.[1] In this document, Volume 2, Task VI - Full-Scale Engine Testing and Task VII - Post-Test Evaluation are covered in detail, including recommendations concerning the future of the exothermic SC casting process and SC HP turbine blades.

The results of Tasks VI and VII--project completion information--are restricted by the NASA For Early Domestic Dissemination (FEDD) policy. The FEDD legend, describing the requirements of this policy, is printed on the cover of this document.

SECTION III

3.0 FULL-SCALE ENGINE TESTING

Scope

The objectives of the Task VI Engine Testing were as follows:

(1) Verify the anticipated reduction in TSFC with the SC turbine blades

(2) Demonstrate the durability of both the material and the design of the new blade. The program required that the HP blades produced in Task V be subjected to 200 hours of typical engine operating conditions in an appropriate GTEC engine.

The Task VI Engine Testing of the fully processed HP turbine blades consisted of back-to-back performance tests followed by four 50-hour endurance test segments chosen by GTEC and approved by NASA. The performance test was designed to compare a production DS turbine configuration with the same engine using the MATE Project 3 SC turbine blades. The four 50-hour test segments, in the order performed, were designed to evaluate the resistance of the SC blade to high-cycle fatigue, stress-rupture, a simulated commercial mission, and low-cycle fatigue. These test conditions were chosen to allow direct comparison of the SC blades produced in this project with the production DS uncooled (solid), MAR-M 247 turbine blades. The test cycles for these four test segments are shown in Figures 1, 2, 3, and 4. The blade substitution schedule presented in Table 1 was used to expose groups of test blades to single and multiple loading conditions established by the test parameters of the four 50-hour tests. This substitution plan permitted comprehensive post-test evaluation of the individual and combined effects of the four test segments by both nondestructive and destructive techniques.

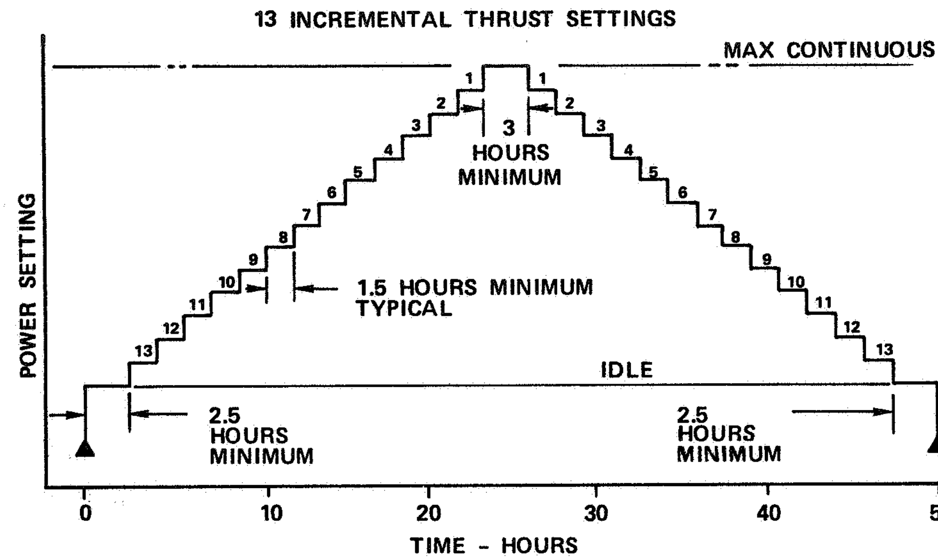

Figure 1. Cycle A: First 50-Hour Test, High-Cycle-Fatigue Evaluation.

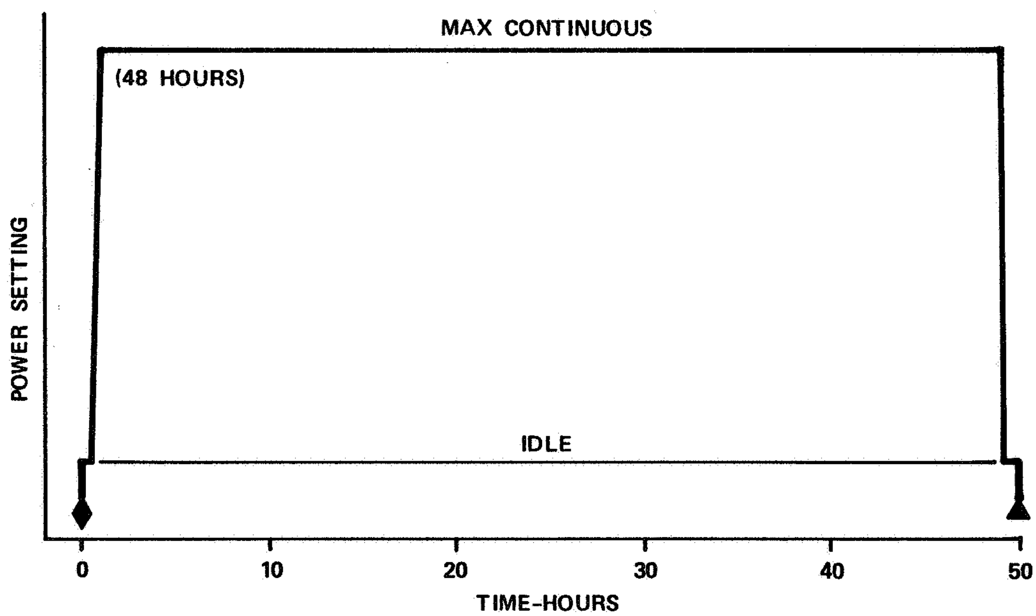

Figure 2. Cycle B: Second 50-Hour Test, Stress-Rupture Evaluation.

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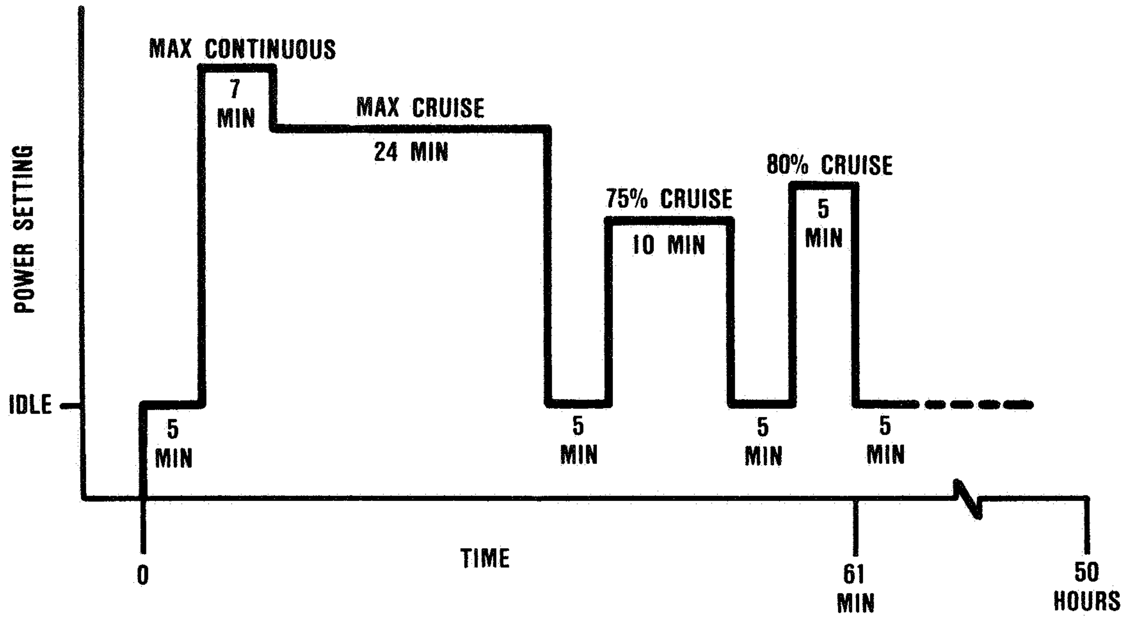

Figure 3. Cycle C: Third 50-Hour Test, Simulated Commuter Aircraft Mission.

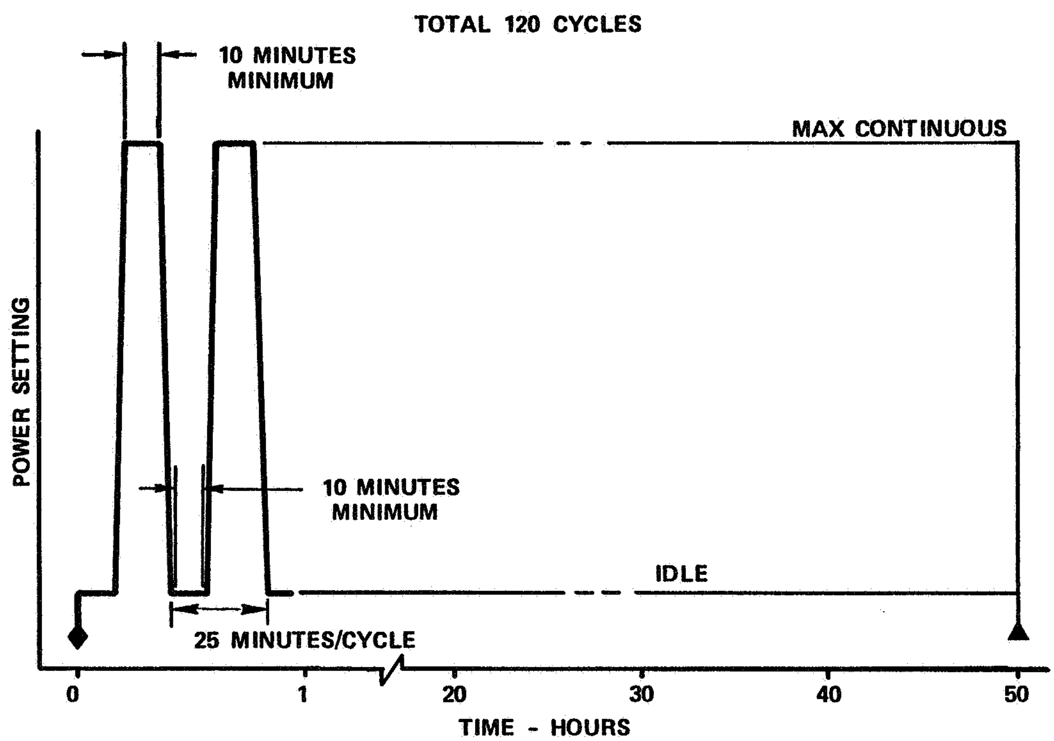

Figure 4. Cycle D: Fourth 50-Hour Test, Low-Cycle-Fatigue Evaluation.

TABLE 1. BLADE SUBSTITUTION PLAN FOR MATE PROJECT 3 ENGINE TEST.

	Number of Blades Substituted for Each Test Cycle										
Material	A	B	C	D	A+B	B+C	C+D	A+D	A+B+C	B+C+D	A+B+C+D	Totals
NASAIR 100		2	2	2	2	2	1	4	1	1	18	35
Alloy 3	2						1		1	1	34	39
Totals	2	2	2	2*	2	2	2*	4*	2	2*	52*	74

A = 50-Hour High-Cycle-Fatigue Evaluation (Figure 1)

B = 50-Hour Stress-Rupture Evaluation (Figure 2)

C = 50-Hour Simulated Mission Evaluation (Figure 3)

D = 50-Hour Low-Cycle-Fatigue Evaluation (Figure 4)

*Blades in engine at end of 200-hours

3.1 Performance Testing

The MATE Project 3 SC HP turbine blade is essentially the same configuration as the production DS turbine blade, except for the addition of a tip winglet and an aft platform flow discourager. To accommodate this new blade design, minor modifications were made to some of the surrounding hardware.

To use the superior temperature capability of the SC materials, cooling air supplied to the fore and aft sides of the HP turbine disk was reduced by blocking part of the cooling air entry holes. Seals were added between the blades to prevent cooling air from leaking out and hot gas from being ingested between the blade platforms, and the firtree seal was eliminated to allow more cooling airflow through the firtree. The net effect of these modifications was to reduce the cooling airflow while maintaining adequate cooling air to the disk and blade firtree.

Back-to-back performance tests were conducted to evaluate the effect of the SC blade and support hardware on the measured engine performance. Testing was done in a fan test cell located in GTEC's Phoenix facility, with standard instrumentation. Figure 5 shows the TFE731 installed in the fan test cell.

Following the standard production engine performance baseline test, the engine was rebuilt to the MATE Project 3 configuration, substituting the following hardware for the original production hardware.

PART NAME
MATE HPT Blades - NASAIR 100
MATE HPT Blades - Alloy 3
ITT Duct
HPT Shroud Segments
LPT Nozzle Duct
Shroud Retaining Sleeve
Aft Curvic Coupling
HPT Seal Plate
HPT Nozzle, 26 Vane

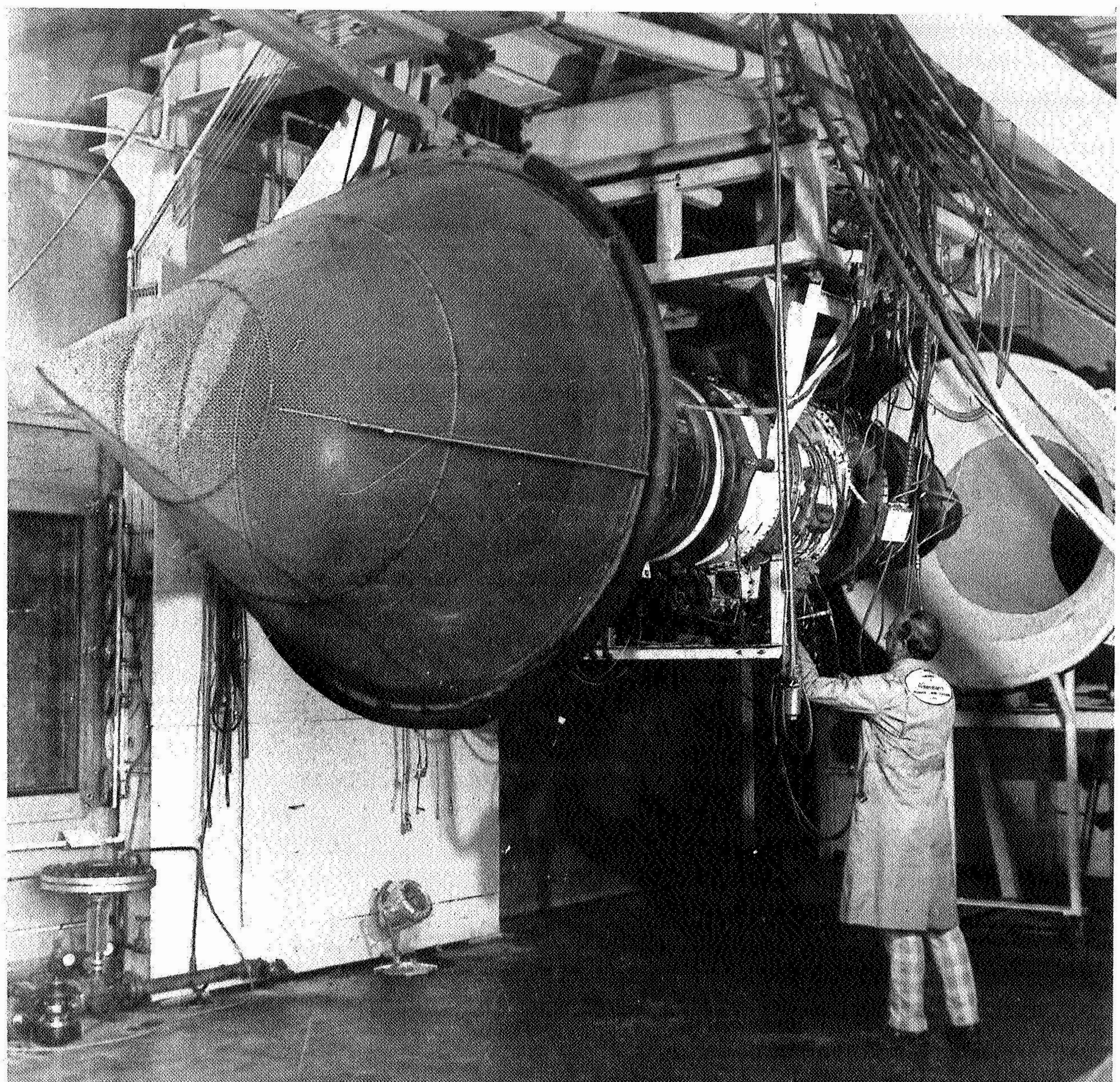

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Figure 5. TFE731 Engine Installed in Phoenix Test Cell.

The engine with this new hardware was then run through the standard performance calibration, using the same test cell and instrumentation that was used for the baseline performance test.

Reduction of the performance data to standard-day conditions indicated the following:

- o The baseline standard engine was well within production test limits.

- o Incorporating the MATE Project 3 SC turbine blades and support hardware into the same engine produced a measured 1.4 percent reduction in TSFC and reduced T_5 by 2.5 percent.

These performance improvements are directly related to the increased efficiency of the MATE HP turbine blade and the decrease in cooling flow.

Upon disassembly of the engine, a slight rub was found at approximately the 2 o'clock position, forward looking aft. Figures 6, 7, and 8 show that the assembly and shroud interference was minor.

Visual and fluorescent penetrant inspection (FPI) was completed after teardown, with no distressed parts identified. Several new blades were substituted for endurance testing, and the wheel was reassembled and balanced for the first endurance test. To avoid further rubs, the ID of the stator shrouds were resized to the maximum diameter allowed for production engines.

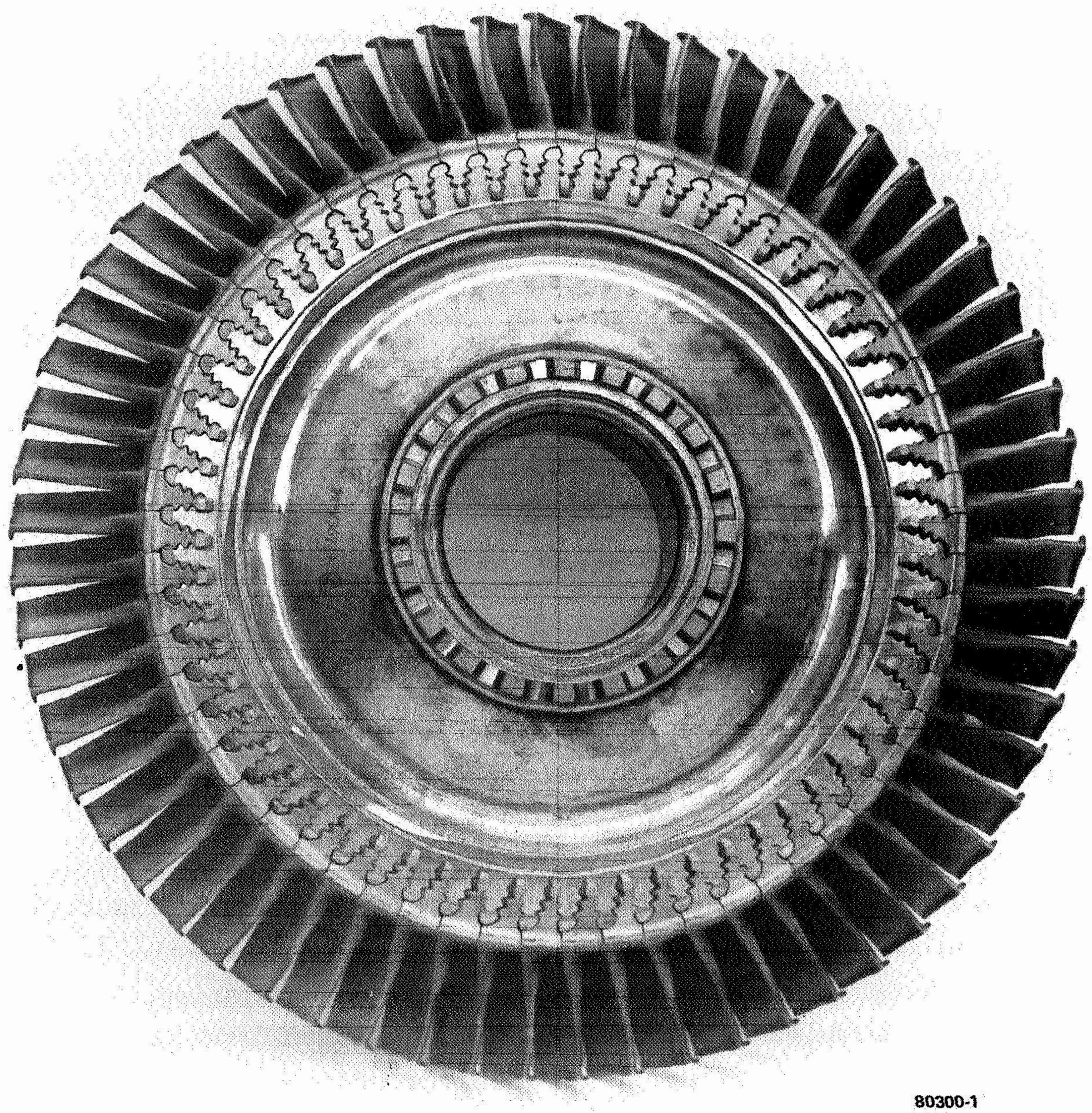

Figure 6. MATE Rotor Assembly After Performance Testing.

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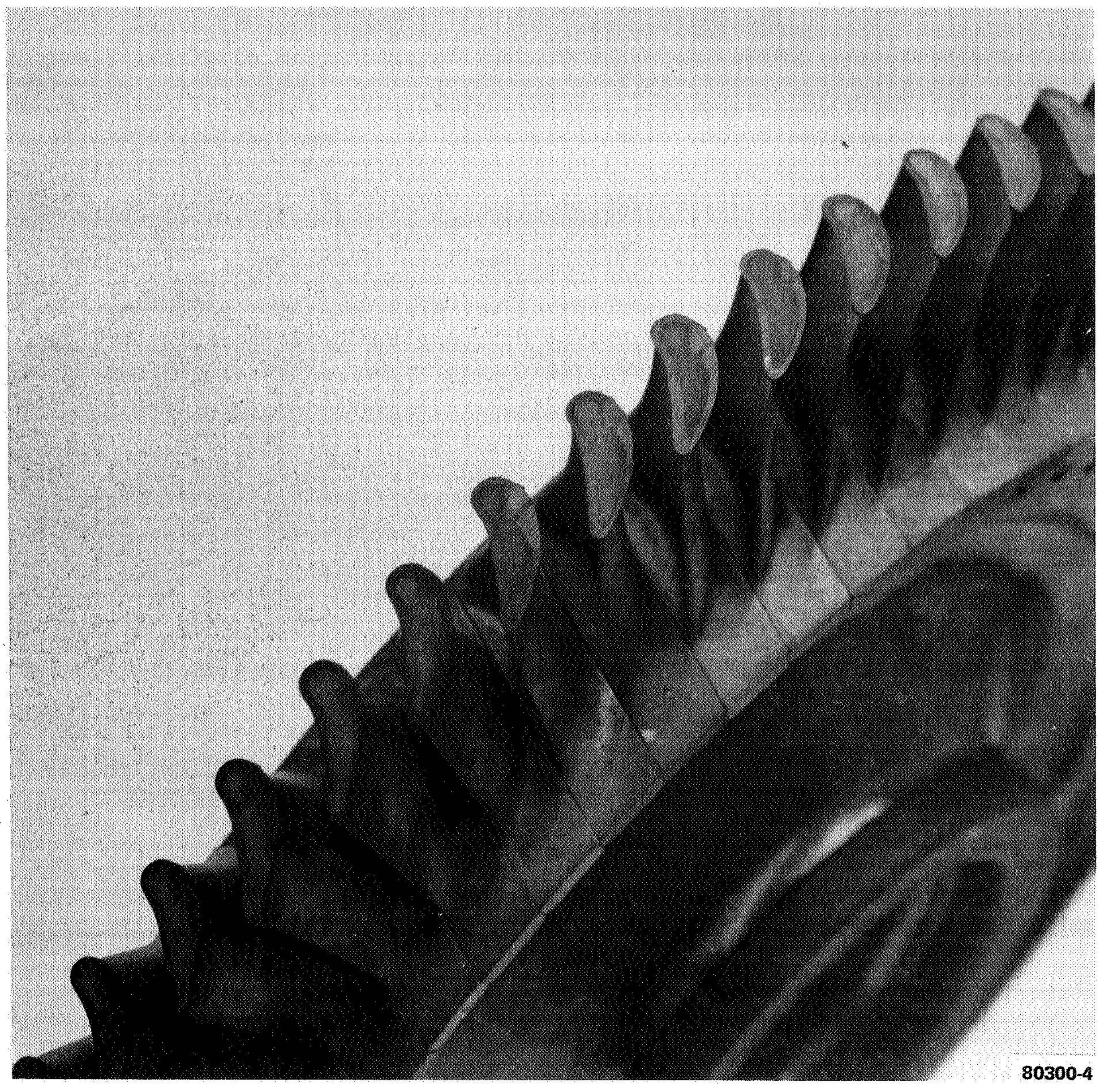

Figure 7. Tip View of MATE Rotor Assembly Following Performance Test.

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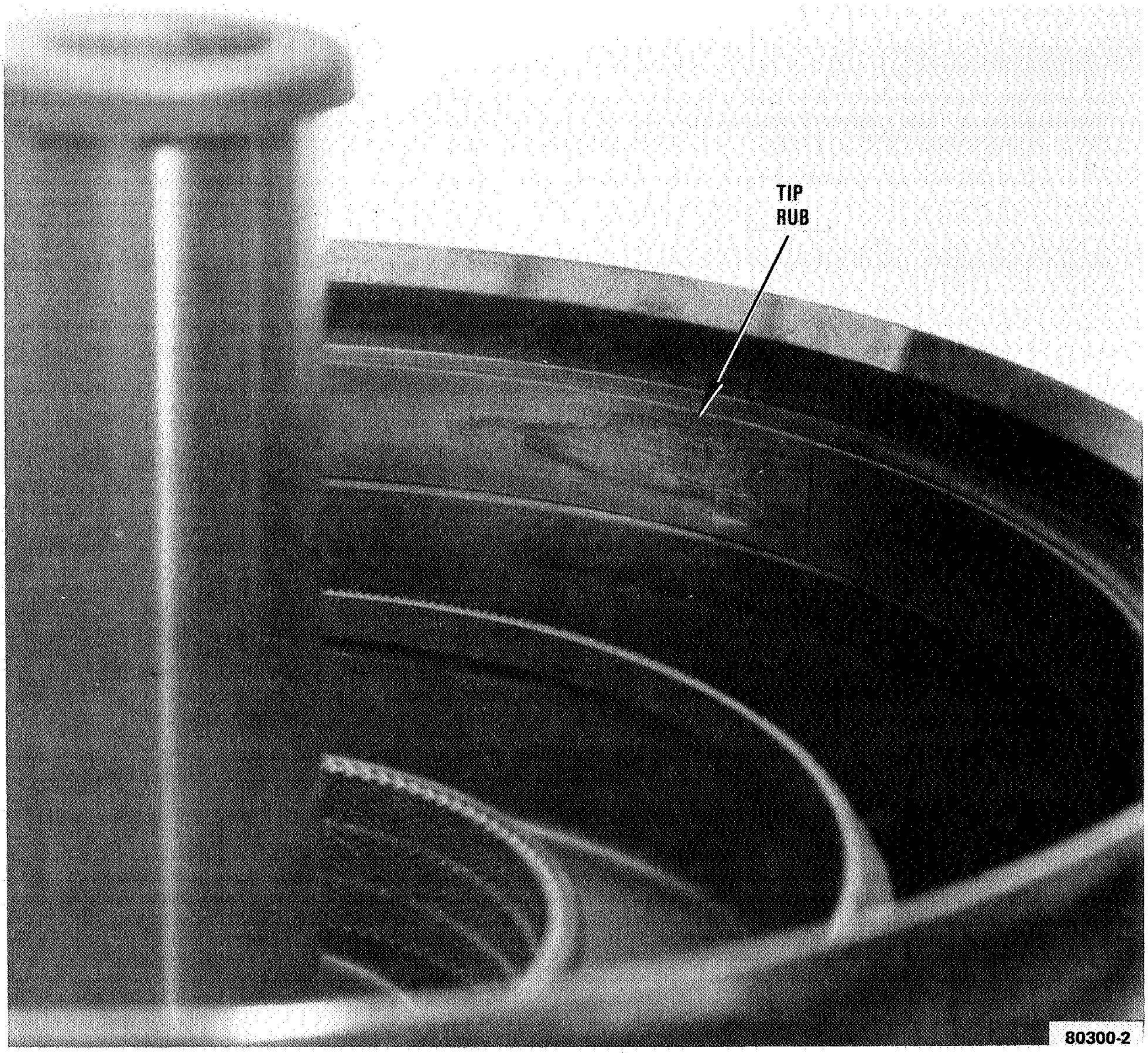

Figure 8. HP Turbine Shroud Following Performance Test of MATE SC Blades.

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3.2 Endurance Testing

Endurance testing was accomplished in four 50-hour test segments with a teardown inspection after each 50-hour test. Figures 1, 2, 3, and 4 (previously shown) represent the four test cycles used during endurance testing. The blade substitution schedule presented in Table 1 was used to expose test blades to various combinations of single and multiple loading conditions to isolate the effects of the various tests on the blades.

All endurance testing was done with standard engine monitoring instrumentation at GTEC's remote test facility located at San Tan, Arizona.

The first 50-hour test cycle was established to verify the MATE Project 3 blade response and evaluate the resistance to high-cycle fatigue (Figure 1). This test was accomplished as scheduled. No operating problems occurred during this test, and all test parameters were within limits. Post-test inspection revealed no distress on any of the SC blades or support hardware. Blades were substituted into the rotor assembly in accordance with the previously established substitution plan, the rotor was rebalanced, and the engine was reassembled for the second 50-hour endurance test.

The stress-rupture endurance test cycle used for the second test was shown previously in Figure 2. Again, no problems were encountered during testing. However, post-test inspection revealed that one blade (S/N N27) had lost approximately fifty percent of the aft flow discourager. Figure 9A is a sketch of the failed blade. No other signs of distress were found on the remaining SC blades, but moderate foreign object damage (FOD) was found on the first and second LP turbine stages.

Detailed examination of the failed blade indicated that the flow discourager web thickness was undersized and contained excessive porosity due to microshrinkage. Preliminary conclusions were that the platform, undersized and weakened by excessive casting porosity, could not carry the centrifugal bending load and failed at the thinnest section. Further details of this blade examination and analysis confirmed the preliminary conclusion and are reported in the post-test-evaluation section of this report.

In addition to the visual and FPI inspections scheduled between endurance tests, the web thickness of each blade was measured and the casting porosity in each web was carefully evaluated. Three blades were eliminated from further testing due to the combination of a thin platform web and excessive porosity.

To avoid any chance of additional platform failures, all remaining blades were reworked (as shown in Figure 9B) to reduce the

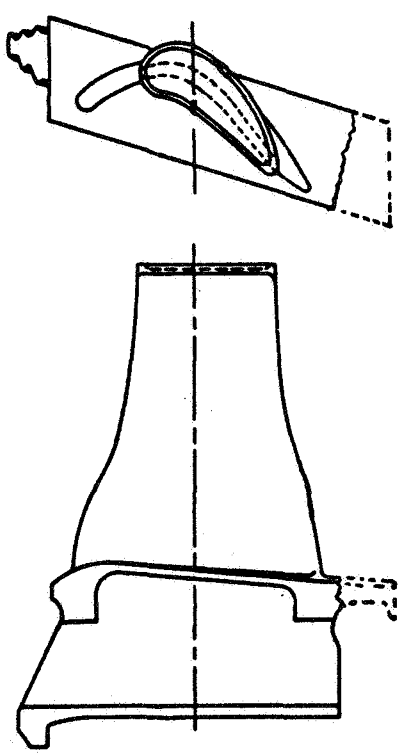

Figure 9A. Sketch Illustrating Flow Discourager Failure in Blade N27 During Second 50-Hour Test.

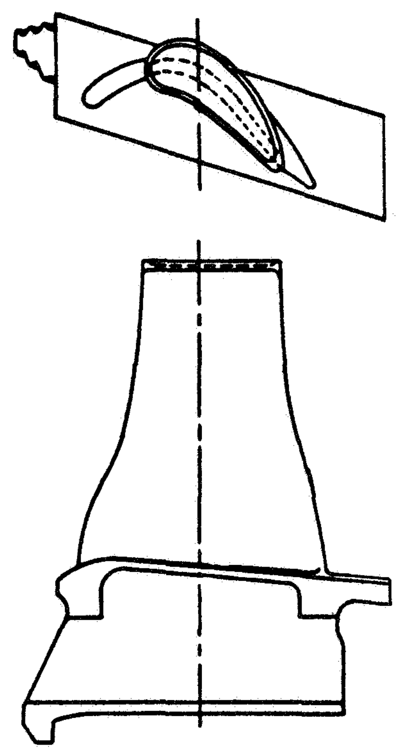

Figure 9B. Sketch Illustrating Flow Discourager Rework.

stress in the flow discourager region. The reworked blades were then reassembled into the disk with blades substituted according to the schedule. The rotor was rebalanced, the damaged LP turbine components replaced, and the engine reassembled for the third 50-hour endurance test.

The third 50-hour test cycle simulated a typical mission for a commuter aircraft (Figure 3). No problems were encountered during this test, and no significant changes in operating parameters were observed as a result of the blade rework. Post-test inspection found no signs of distress in the blades or any other component. Blade substitutions were again made according to the schedule, the wheel rebalanced, and the engine reassembled for the fourth and final 50-hour test.

The fourth 50-hour test cycle, designed to provide an evaluation of the low-cycle-fatigue capability of the SC blades, is shown in Figure 4. Normal accelerations and decelerations were maintained for all cycles. No significant engine test problems were encountered during this test, and engine performance remained consistent with previous testing. The post-test inspection did not reveal any discrepancies in the SC blades or any other hardware. Figures 10 and 11 show typical leading and trailing edge views of blades tested for the entire 200 hours.

Detailed examinations of sample test blades were accomplished according to the scheduled evaluation. Results of these inspections are presented in the post-test evaluation section of this report.

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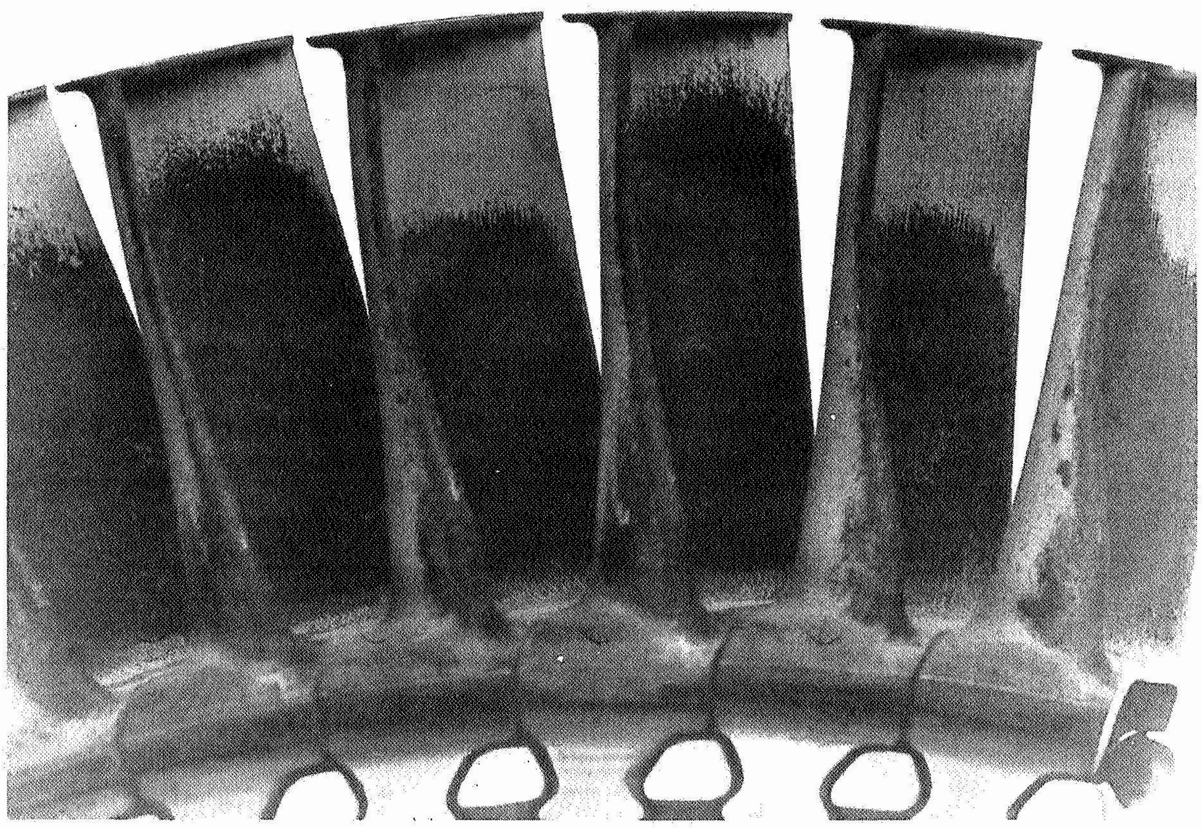

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Figure 10. Leading-Edge View of Typical Blades Subjected to the Entire 200 Hours of Endurance Testing.

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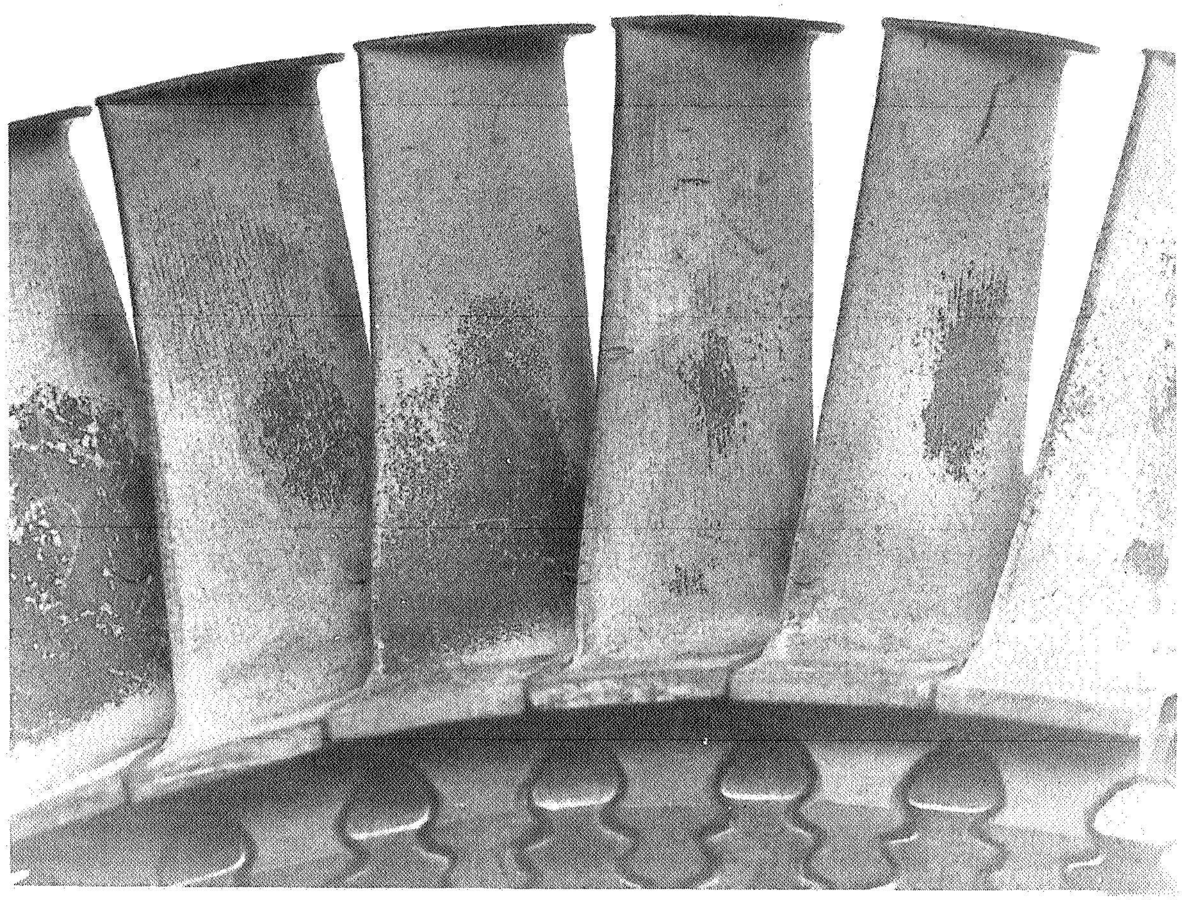

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Figure 11. Trailing-Edge View of Typical Blades Subjected to the Entire 200 Hours of Endurance Testing.

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SECTION IV

4.0 POST-TEST EVALUATION

4.1 Interim-Test Blade Evaluation

After 100 hours of testing (Cycles A and B), routine examination of the HP turbine rotor indicated that one of the SC NASAIR 100 blades (S/N N27) had lost part of the aft flow discourager. The weight of the missing piece was estimated at about one gram. To identify the cause of this flow discourager failure and to document the microstructure of the airfoil, this blade was visually and metallurgically examined. These examinations (Figures 12 and 13) revealed that the flow discourager web thickness was significantly below the minimum specified drawing thickness and only about 65 percent of the average web thickness. The portion of the platform web that failed also had very high amounts of oxidized (surface connected) porosity.

FPI and visual inspection of the remaining blades indicated that comparable platform porosity was present in many of the blades. However, no other blades had the excessive platform porosity and below minimum web thickness that combined to produce a failure.

Microstructural analysis of blade S/N N27 at other locations on the blade was also performed (Figures 13 and 14). This analysis indicated that the SC NASAIR 100 blade had been solution heat-treated at the upper end of the solution heat-treatment window. The eutectic gamma prime phase was completely solutioned and minor incipient melting was observed in the blade root. Substantially less microporosity was noted in the airfoil than in the blade root. Energy dispersive X-ray (EDX) analysis was used to verify the NASAIR 100 composition of blade S/N N27.

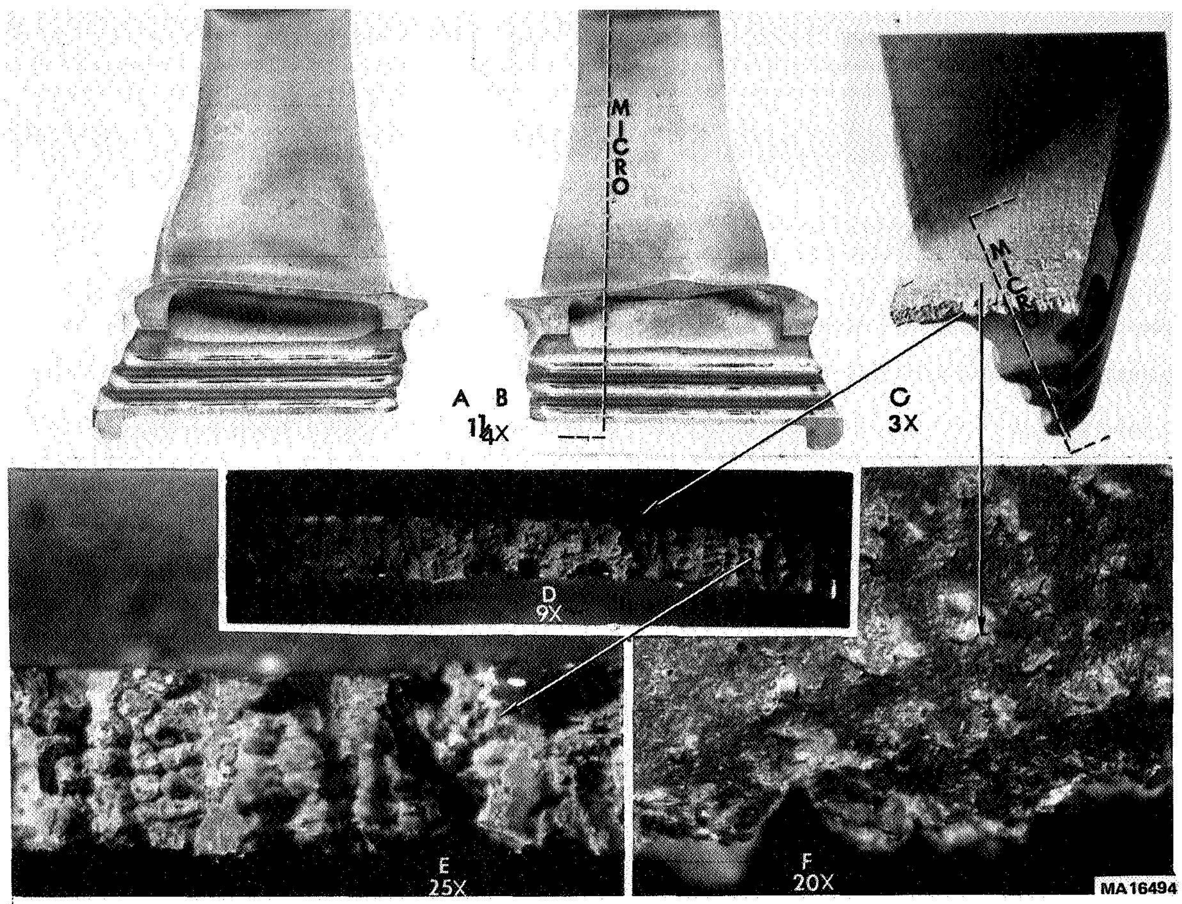

Figure 12. Visual Examination of SC NASAIR 100 Blade (S/N N27) Confirms that Substantial Porosity and a Very Thin Platform Web Contributed to an Overload Fracture of the Flow Discourager Tooth During the Second 50-Hour (Maximum Continuous Power) Segment of the Engine Test. (Photographs are 75 percent of indicated magnifications.)

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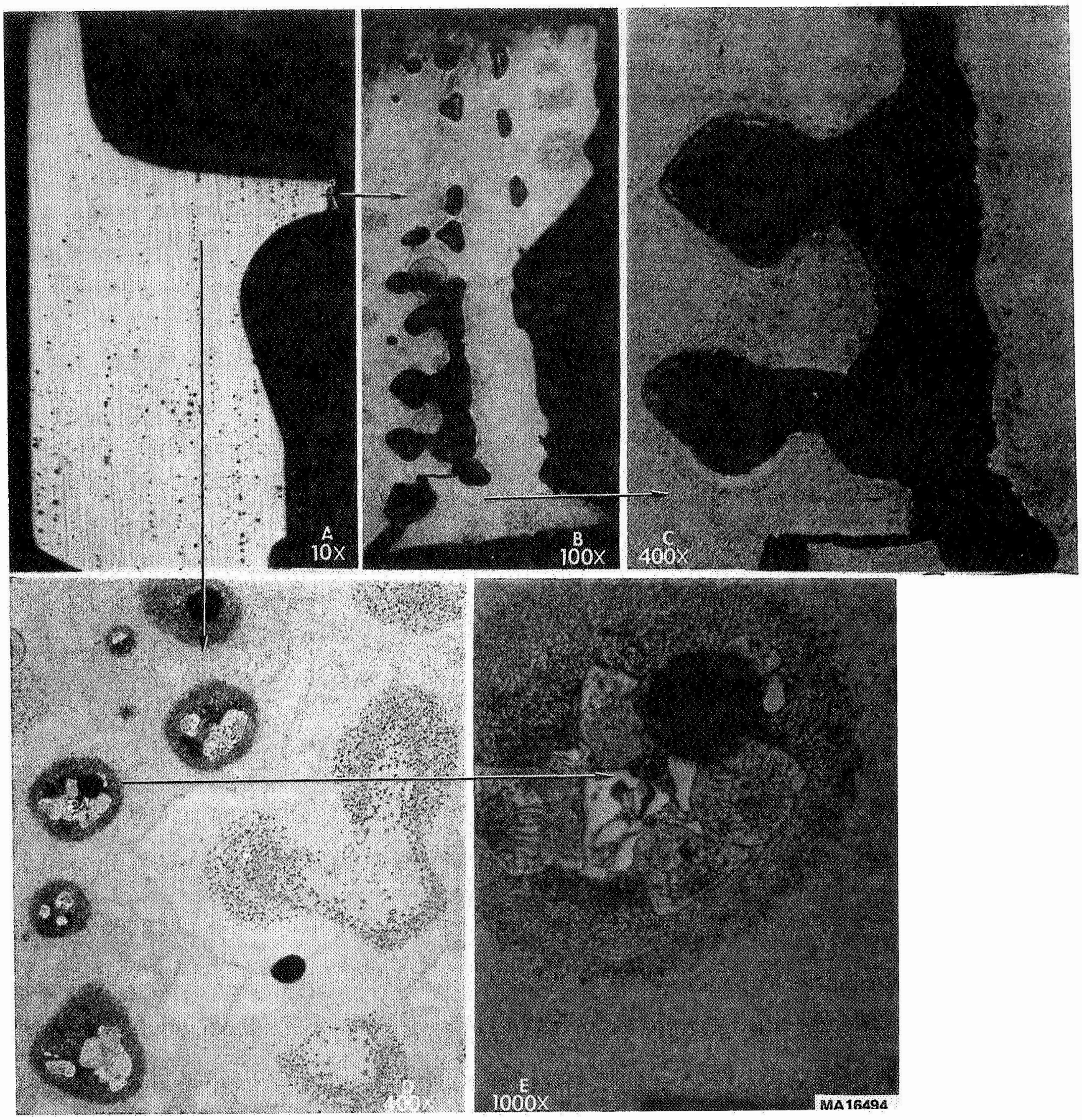
INTERCONNECTED POROSITY



INCIPIENT MELTING

Figure 13. Extensive Interconnected and Oxidized Porosity (top) and Incipient Melting (bottom) Were Present in the NASAIR 100 Adjacent to the Failed Platform Web (SC NASAIR 100 Blade S/N N27). Photographs are 85 percent of indicated magnifications.

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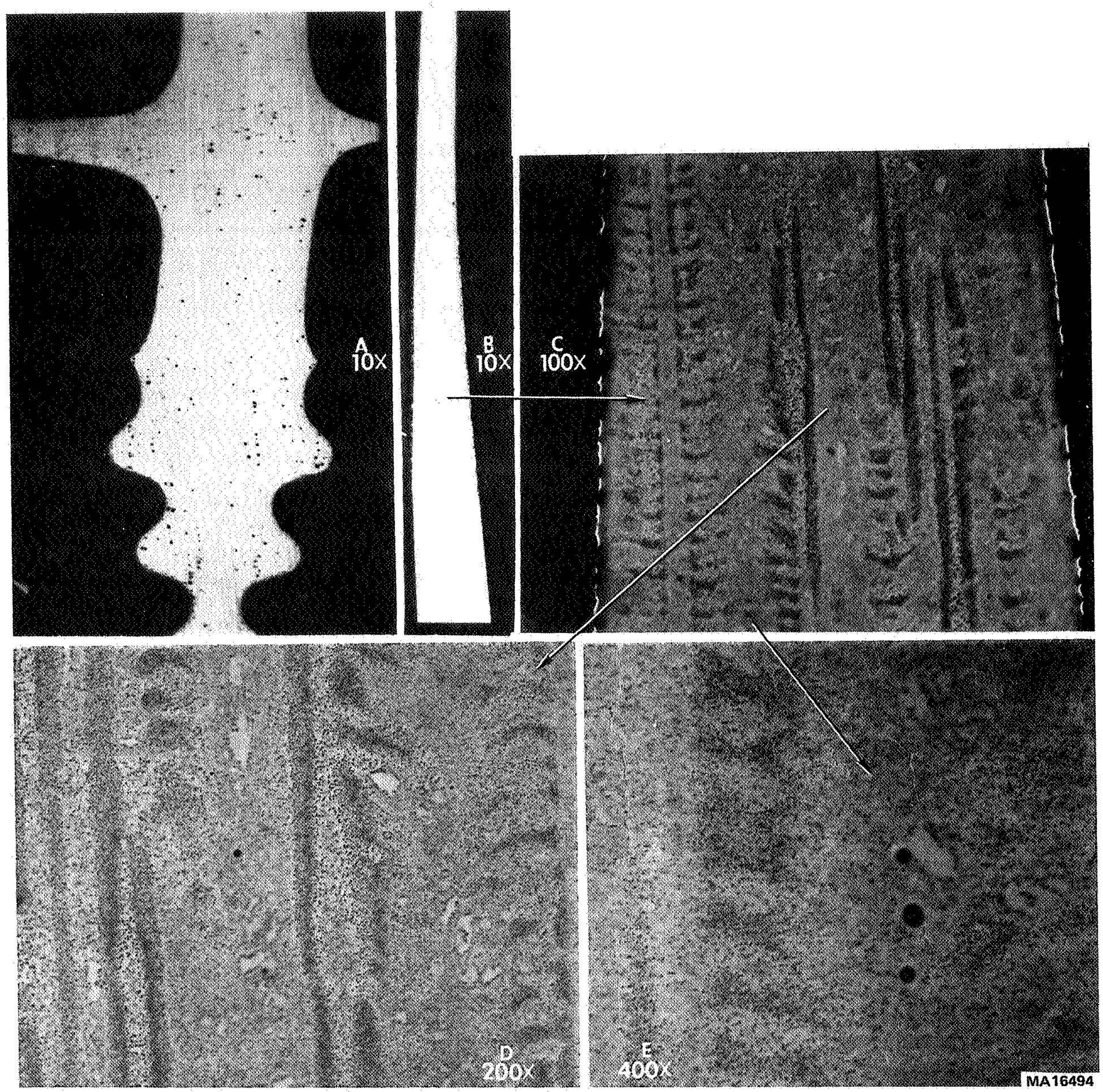

Figure 14. Airfoil of Blade S/N N27 Exhibited a Microstructure Typical of Fully Processed SC NASAIR 100. (Photographs are 80 percent of indicated magnifications.)

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4.2 Post-Test Blade Evaluation

Following the removal of the flow discourager tooth edge from the remaining SC blades (described previously in this report), the last two test cycles (C and D) were completed without incident. At the completion of the required 200 hours of testing, all NASAIR 100 and Alloy 3 turbine blades were carefully examined by both FPI and visual inspection at magnifications up to 40X. No evidence of distress was noted on any of the blades.

In addition to the FPI and visual inspections, three SC NASAIR 100 blades (S/N N20, N33, and N48) and one SC Alloy 3 blade (S/N A42), which had been exposed to the full 200 hours of the engine test, were selected for metallographic examination. The appearance of the blades at the conclusion of the test and the location of the longitudinal metallographic section are provided in Figure 15.

Results of the examination of the SC Alloy 3 blade S/N A42 are provided in Figure 16. Metallographic examination indicated that the single-crystal alloy was fully solutioned with no evidence of incipient melting. Minimal porosity was observed in the airfoil, with higher amounts present in the blade root. Scanning electron microscopy (SEM) indicated that the cubic gamma prime precipitate morphology was retained in the blade root and the minimally stressed tip region of the airfoil. In contrast, the cubic gamma prime phase transformed to platelets aligned perpendicular to the applied centrifugal stress in the [001] direction in the higher temperature portion of the airfoil. Data in the literature indicates that this gamma prime morphology, commonly known as rafting, occurs at low creep strains and reduces subsequent creep rates.[2,3] Rafting of the gamma prime phase in the airfoil was the only metallurgical modification associated with operation in this engine.

Post-test metallographic analysis of the SC NASAIR 100 blades indicated that they had been solution heat-treated at the upper limit of the heat-treatment window. The eutectic gamma prime had

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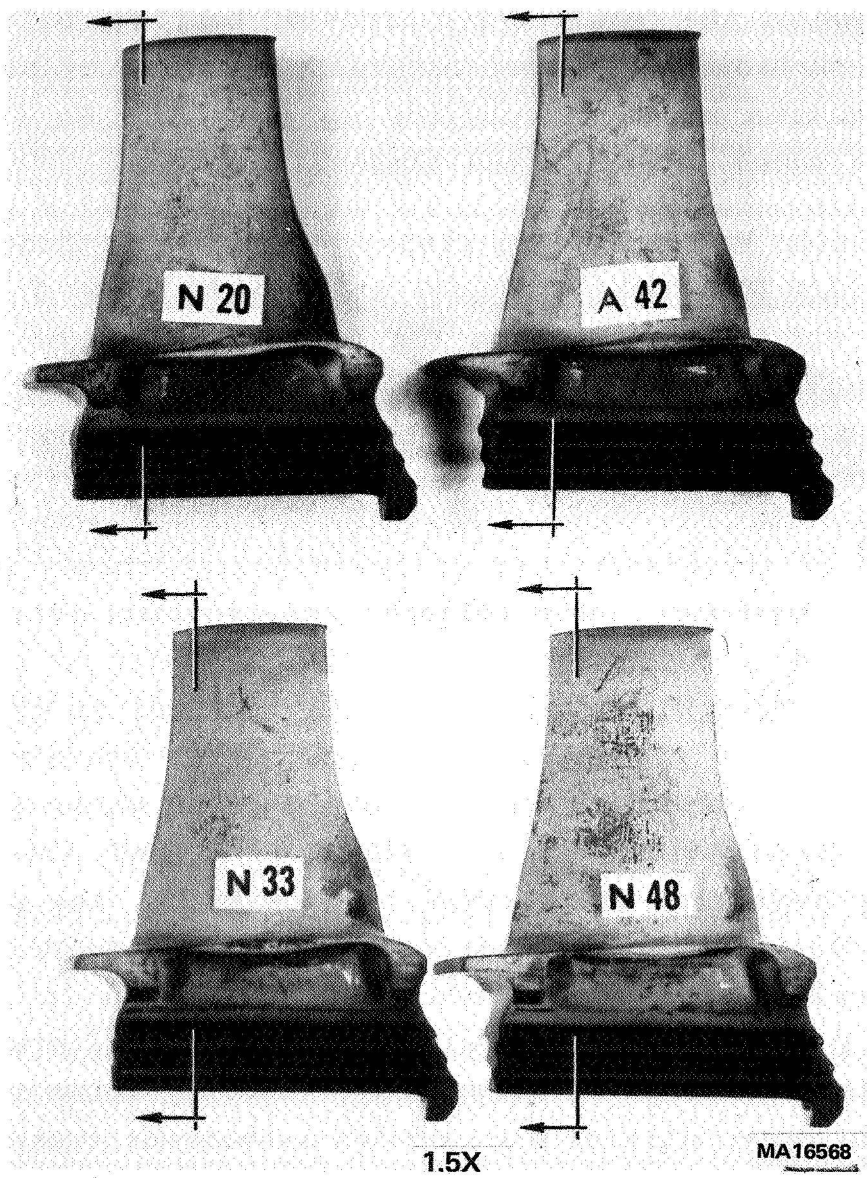

Figure 15. Visual Appearance of SC NASAIR 100 (S/N N20, N33, N48) and SC Alloy 3 (S/N A42) Blades after the 200-Hour Engine Test. Vertical Lines Indicate Location of Longitudinal Metallographic Section.

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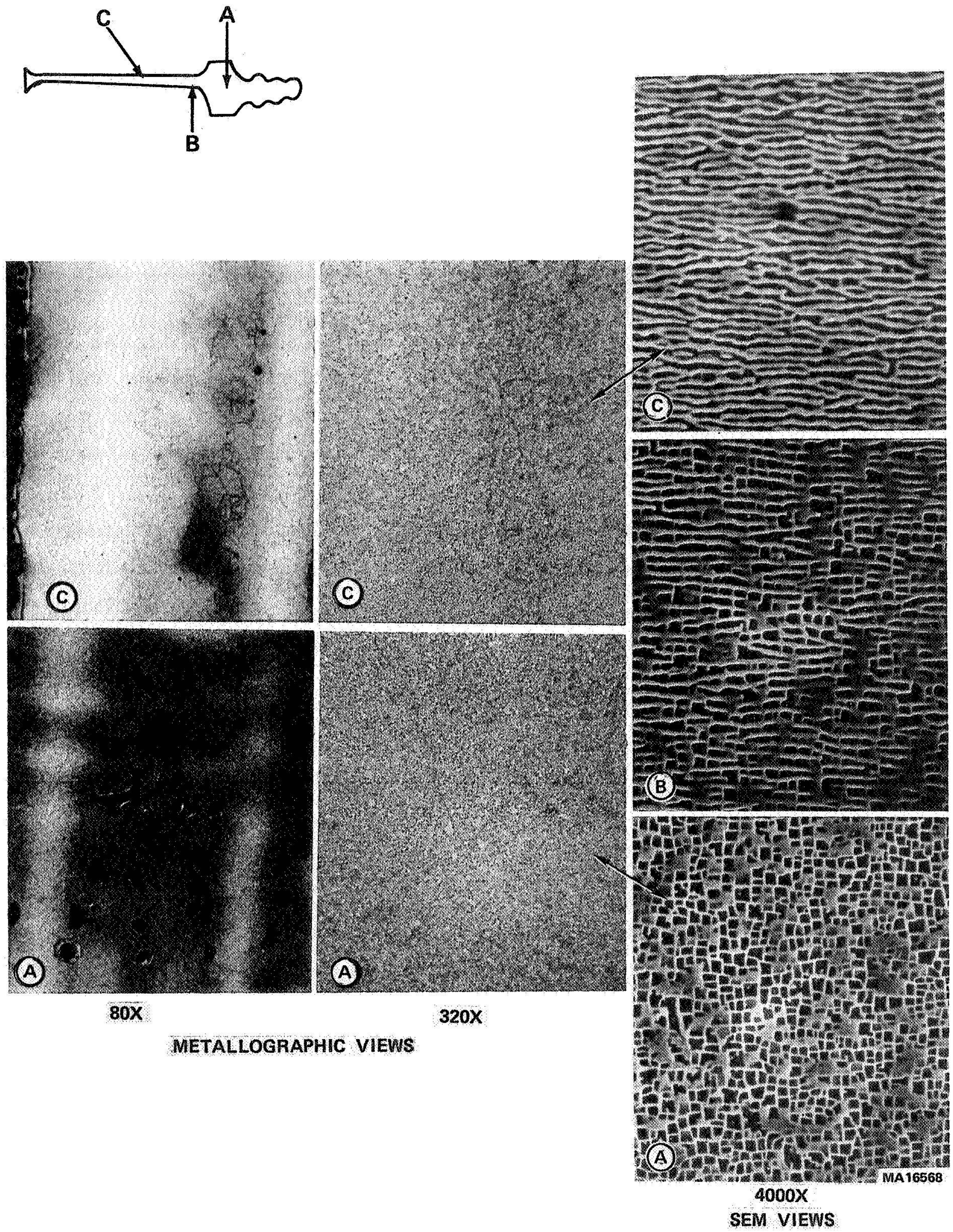

Figure 16. Microstructure of SC Alloy 3 HP Turbine Blade (S/N A42) after 200-Hour Engine Test.

been completely solutioned, and some indications of incipient melting were observed in the three blades examined. Results of the microstructural examination of Blade S/N N48 illustrate this condition (Figure 17). In some instances, the amount of incipient melting slightly exceeded the one-volume percent permitted by the SC NASAIR 100 specification (see Volume 1).[1] This condition, however, did not affect the performance of the blades in the engine test.

SEM examination of the SC NASAIR 100 blades indicated that the gamma prime phase had undergone modifications similar to the SC Alloy 3 material. As shown in Figure 18, the gamma prime phase had rafted in the central region of the airfoil. The morphology of the rafted gamma prime phase is similar to that reported by Nathal and Ebert[3] for NASAIR 100 at the initiation of secondary (steady-state) creep. The cubic gamma prime phase morphology, which is typical of a fully processed casting, was retained in the relatively cool blade root and in the lightly stressed, but hotter, airfoil location near the blade tip.

Two types of minor secondary phases were also observed in the SC NASAIR 100 turbine blades. A blocky alpha-tungsten phase, which is present in as-cast blades, was observed throughout the root, airfoil, and tip (Figures 17 and 18). This phase is shown in a high magnification SEM photograph in Figure 19. As expected, the nickel-tungsten-rich Mu phase was also observed in the hotter airfoil sections of the SC NASAIR 100 blades after the 200-hour engine exposure (Figure 20). The Mu phase was most commonly observed in the airfoil section, where the rafted gamma prime phase was well developed (see Figures 18, 20).

It should be noted that extensive long-term testing of SC NASAIR 100 specimens (see Volume 1) indicated that the Mu phase, in the amounts observed, was innocuous.[1] Consistent with this information, the Mu phase did not adversely affect the integrity of the SC NASAIR 100 HP turbine blades during the 200-hour engine test.

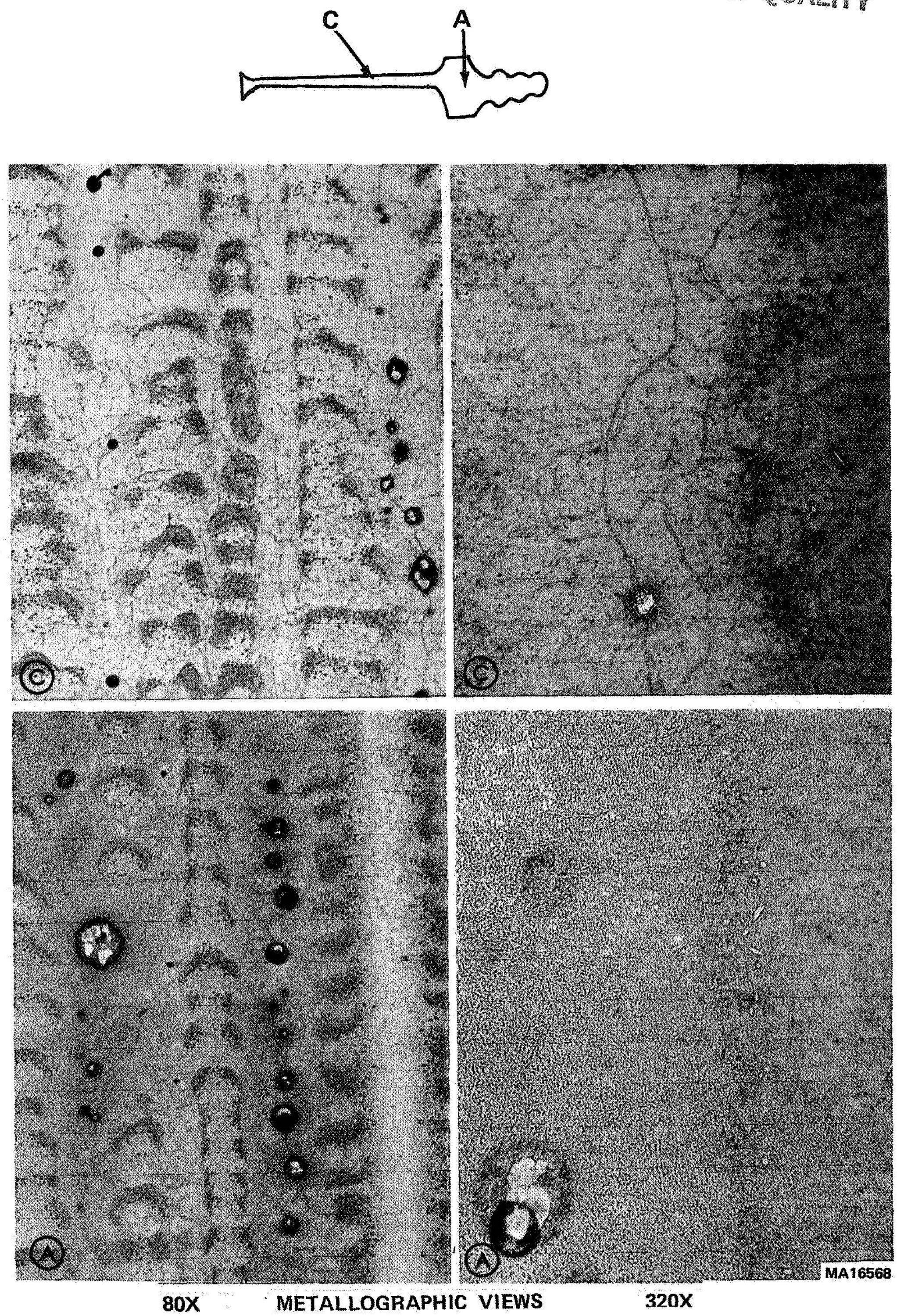

Figure 17. Microstructure of SC NASAIR 100 HP Turbine Blade (S/N N48) after 200-Hour Engine Test.

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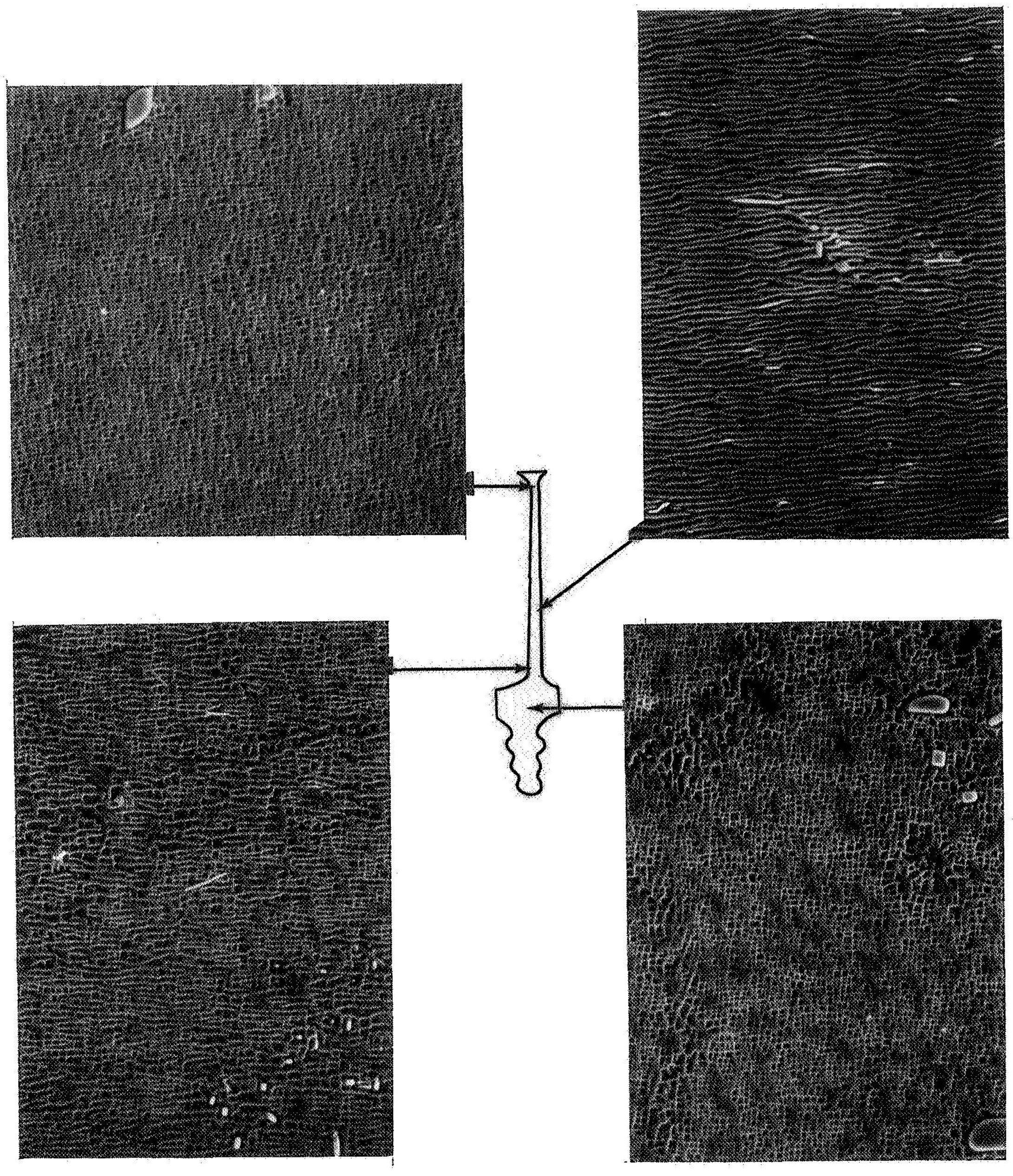

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Figure 18. Scanning Electron Microscope Photographs (2000X) of SC NASAIR 100 HP Turbine Blade after 200-Hour Engine Test (S/N N48).

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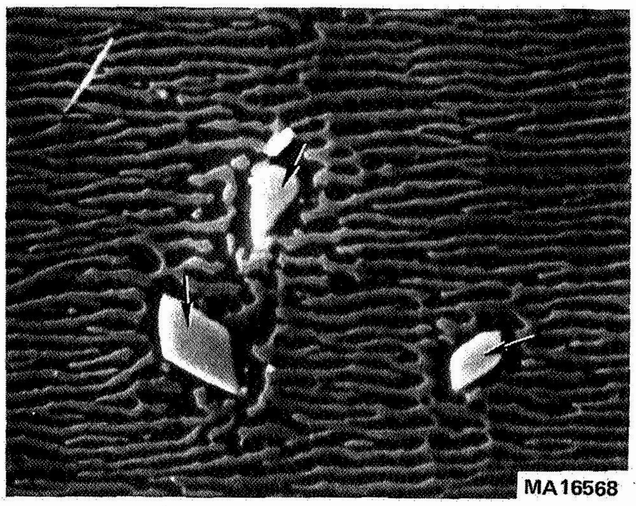

Figure 19. Appearance of the Blocky Alpha-Tungsten Phase (Arrows) in Airfoil Section of SC NASAIR 100 HP Turbine Blade.

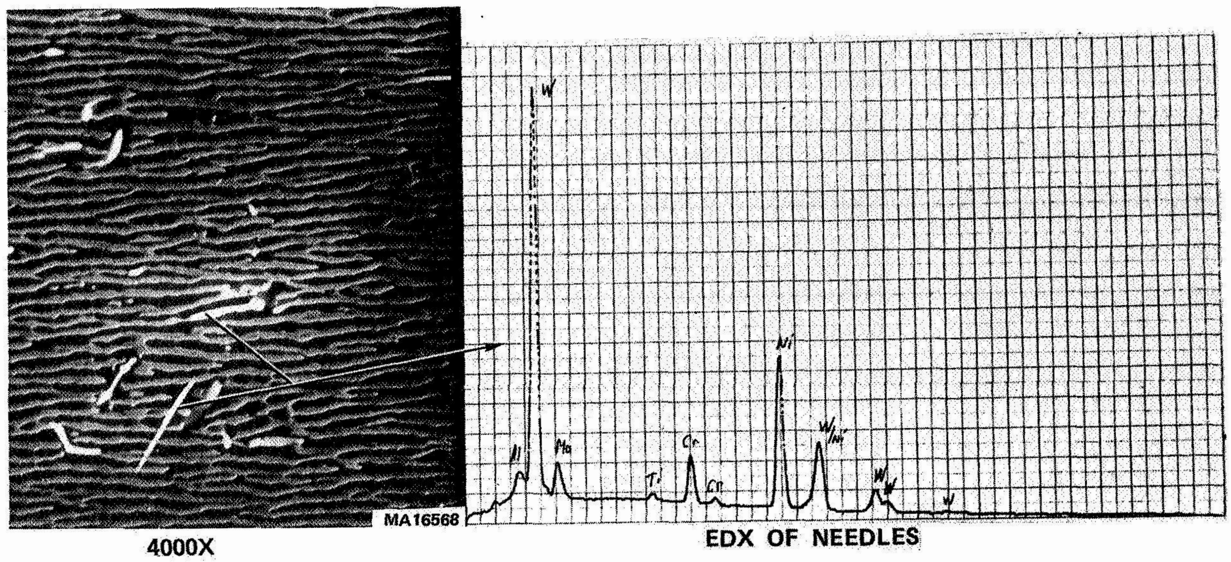

Figure 20. SEM Photograph and EDX Analysis of the Tungsten+ Nickel Rich Mu Secondary Phase in the Airfoil Section of an SC NASAIR 100 Blade (S/N N48) after 200 Hours of Successful Engine Testing.

SECTION V

5.0 CONCLUSIONS

The following conclusions were based upon the results of the engine testing and post-test analysis of the SC turbine blades presented in this report:

- Incorporating the MATE HP turbine blades and support hardware into the test engine reduced TSFC by 1.4 percent and T_5 by 2.5 percent compared to a baseline engine with directionally solidified HP turbine blades.

- The MATE single-crystal turbine blades, both NASAIR 100 and Alloy 3, showed no signs of distress after successfully completing over 200 hours of endurance engine testing.

SECTION VI

6.0 RECOMMENDATIONS

After completion of the engine testing and the post-test evaluation of the SC turbine blades, the following recommendations can be made:

- Blade Design - The SC blade performed well in the engine test, both from efficiency and durability standpoints. The only change recommended is a review of the aft flow discourager design. Better thickness control or a change in thickness is required if the tolerances between the cast outer surface or the machined inner surface cannot be reduced.

- Process Control Plan - Due to the changes in the investment casting industry since this project was initiated, it is recommended not to pursue further development of the exothermic SC process. The major casting houses have already made the capital investment in withdrawal equipment, thus eliminating one advantage of the exothermic process. Therefore, unless the proprietary aspect of the SC withdrawal process becomes a significant problem, further development of the exothermic process is not recommended.

- Property Specifications and Blade Acceptance Criteria - No changes are recommended in either of these items at this time. However, these areas are constantly reviewed and compared to engine test experience. Thus, changes in either or both may be desired as the GTEC experience base grows.

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16. Abstract

The overall objectives of Project 3 were to develop the exothermic casting process to produce uncooled single-crystal (SC) HP turbine blades in MAR-M 247 and higher strength derivative alloys and to validate the materials process and components through extensive mechanical property testing, rig testing, and 200 hours of endurance engine testing.

These Program objectives were achieved. The exothermic casting process was successfully developed into a low-cost nonproprietary method for producing single-crystal castings.

Single-crystal MAR-M 247 and two derivative DS alloys developed during this project, NASAIR 100 and SC Alloy 3, were fully characterized through mechanical property testing. SC MAR-M 247 shows no significant improvement in strength over directionally solidified (DS) MAR-M 247, but the derivative alloys, NASAIR 100 and Alloy 3, show significant tensile and fatigue improvements.

Firtree testing, holography, and strain-gauge rig testing were used to determine the effects of the anisotropic characteristics of single-crystal materials. No undesirable characteristics were found. In general, the single-crystal material behaved similarly to DS MAR-M 247. Two complete engine sets of SC HP turbine blades were cast using the exothermic casting process and fully machined. These blades were successfully engine-tested.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Turbine-Blade	Columnar-Grain	[redacted]
Single-Crystal	MAR-M 247	
Alloy-Selection	NASAIR 100	
Ni-base Alloys	Alloy 3	
Investment Casting		
Exothermic-Heating		

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